Producing Nuclear Recoils

Coherent Neutrino-Nucleus Scattering Workshop

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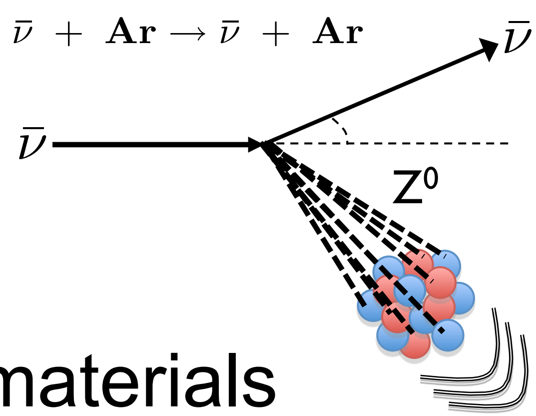


Outline

- The need to characterize detector materials
- Mechanisms for producing nuclear recoils
- Considerations for experimental design
- Two experimental designs for LAr
  - Collimated & filtered ^{7}Li(p,n)^{7}Be
  - Nuclear resonance fluorescence (NRF)

We need to characterize detector materials

$$\frac{d\sigma}{d(\cos\theta)} = \frac{G^2}{8\pi}[Z(4\sin^2(\theta_w)-1)+N]^2 E_\nu^2(1+\cos\theta)$$

$$E_r = \frac{E_\nu^2[1-\cos(\theta)]}{M_{nucleon}A}$$

$$\langle E_r \rangle = 716eV \frac{(E_\nu / MeV)^2}{A}$$

- We must understand the response of detector materials to the CNNS signal
  - Validation of candidate materials
  - Detector response functions
  - Appropriate scaling of detectors
  - Backgrounds

Average recoil energy for several neutrino energies (eV)

	1.44 MeV	5 MeV	30 MeV
Si	50	640	23000
Ar	35	450	16000
Ge	20	250	9000
Xe	10	130	4700

CNNS acts on the nucleus and so must we

Traditional

- Neutron scatter
  - Mono-energetic
  - Filtered
  - TOF
  - Tagged
  - End-point
  - Spectrum
- Radiative capture
  - Thermal neutron source
  - Cooperative nuclear structure
- Inelastic neutron scatter
  - Shoulder on gamma peak

Non-traditional

- Photo-nuclear scatter
  - Rayleigh
  - Delbruck
  - Thomson
  - NRF
- Charged particle scatter

There is no silver bullet

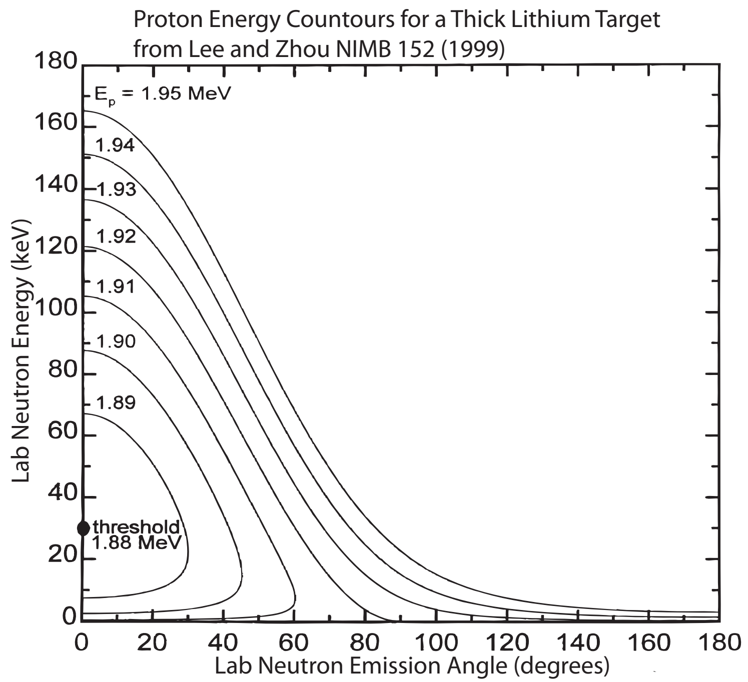
- Target nuclei and neutrino source define energy range
- Separate detectors likely built for material characterization
  - Deployed detectors require comprehensive shielding
  - Characterization detectors need radiation to penetrate
- Characterization must compliment detector design
  - Cross-sections, attenuation, multiple scattering, etc…
- Different detector technologies, different geometries, different concerns
  - Self shielding, room returns, etc…

Two experiments for our LAr detector

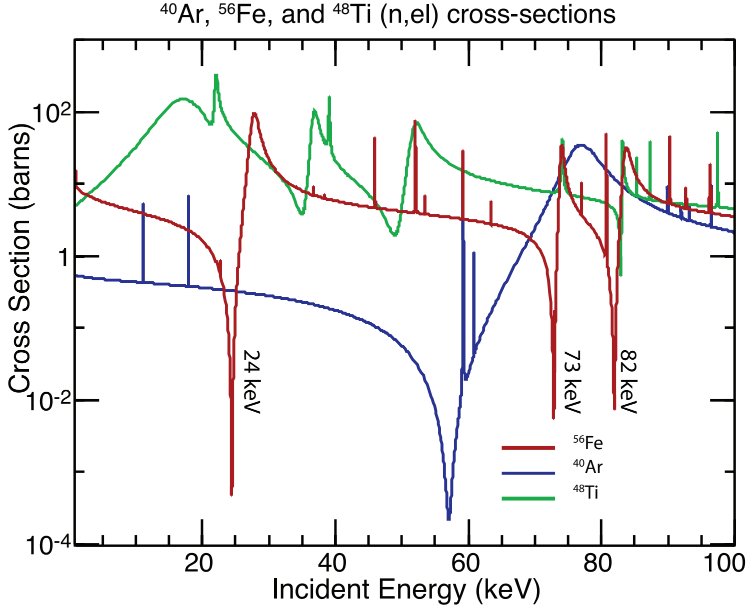
- $^{7}Li(p,n)^{7}Be$, collimated & filtered
  - Exploiting near-threshold kinematics
  - Utilizing “interference notches” in (n,el) cross-sections
    - — Barbeau et al. NIMA 2007
  - 73 keV & 24 keV neutrons
  - End-point and tagged
- Nuclear Resonance Fluorescence (NRF)
  - Several candidate states in ^{40}Ar
  - Sub-keV accessible in detail
    - — T.H.Y. Joshi NIMA 2011

$^7Li(p,n)^7Be$ near-threshold kinematics

Using near-threshold kinematics we can control maximum neutron energy

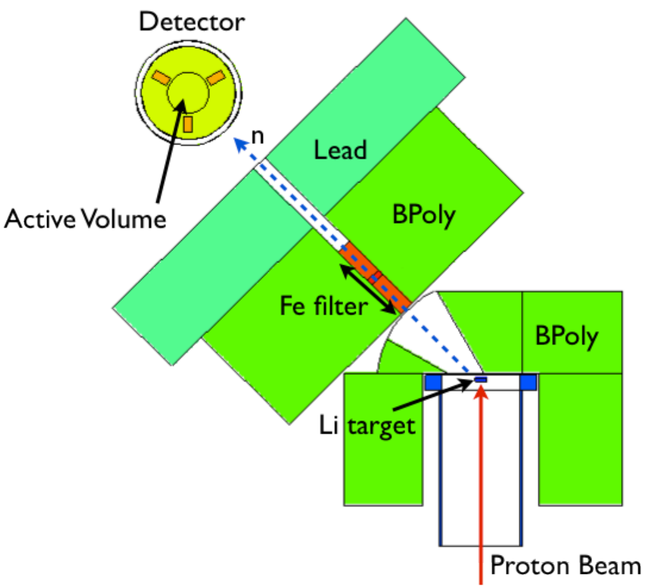


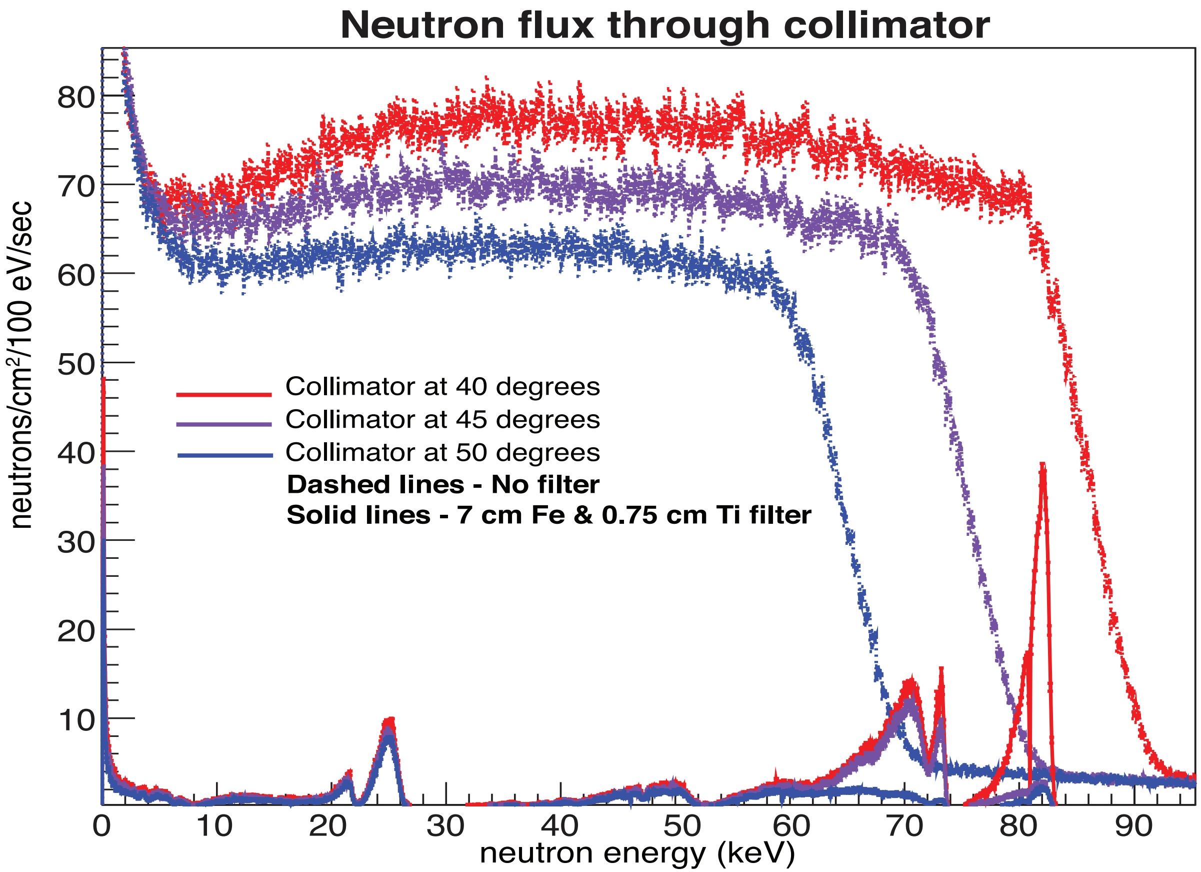
Taking advantage of nuclear data we selectively transmit neutrons through interference dips in scattering x-sections



The 73 keV notch in ^{56}Fe was selected to target the lower energy portion of the (n,el) resonance in ^{40}Ar

Expected thick Li performance 1.93 MeV protons at 1 μA

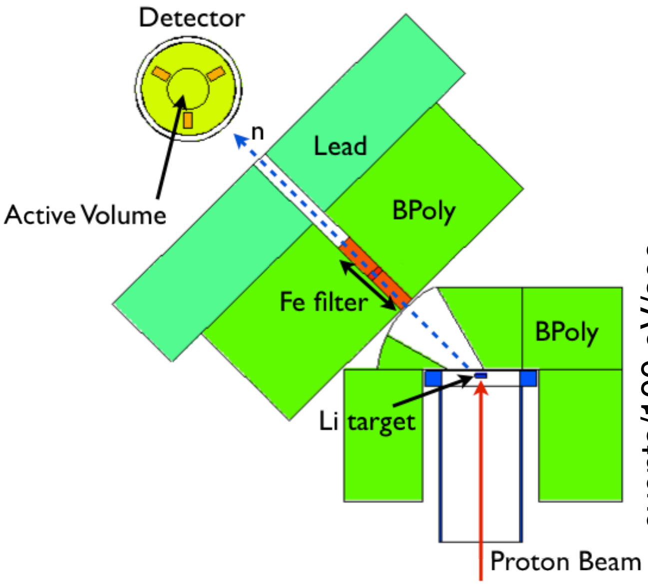


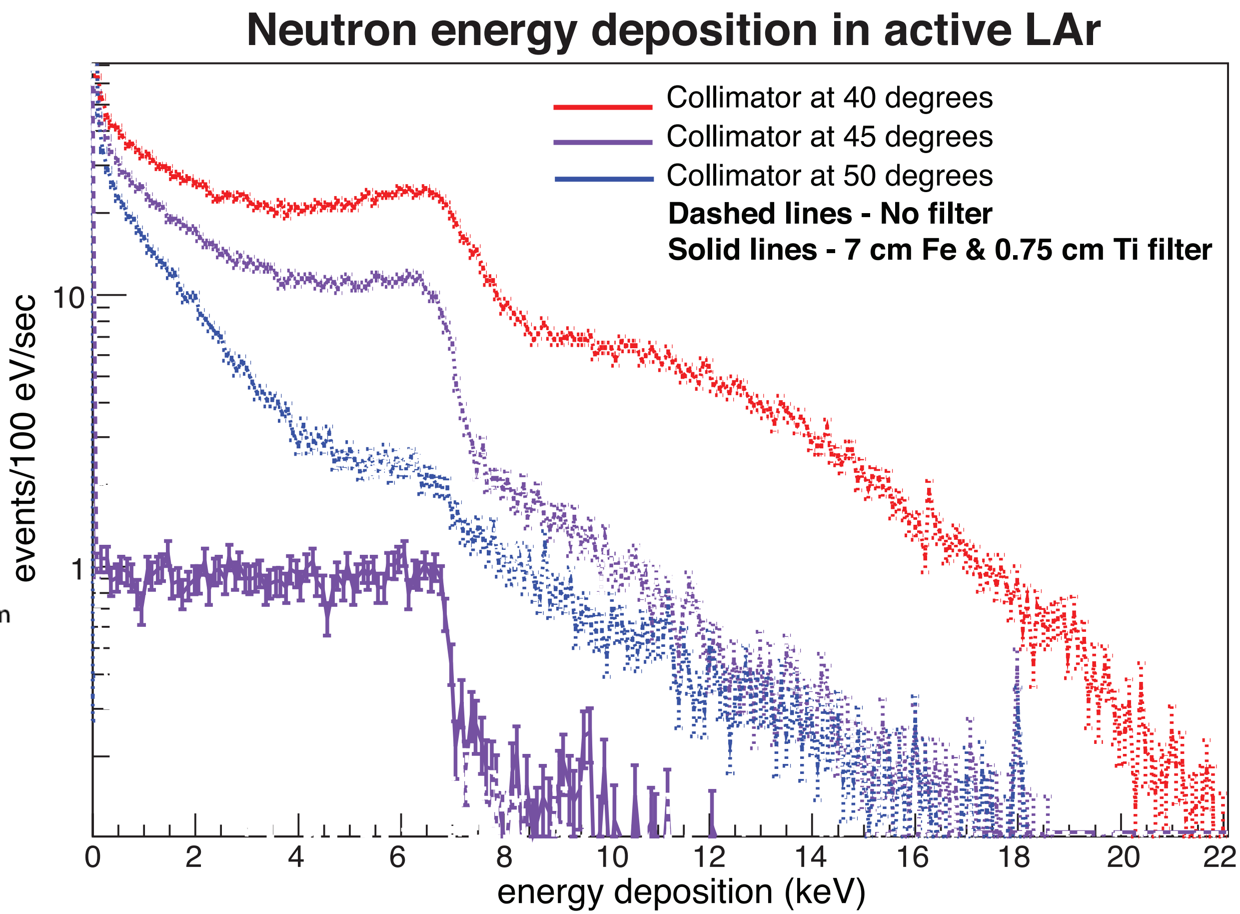


Thin Li target would further improve this design

Dip in 73 keV transmission is a result of scattering by ^{54}Fe

Expected thick Li performance 1.93 MeV protons at 1 μA





Without filtering near-threshold reaction combined with angular tuning can produce a ‘shoulder’ but multiple scattering and detector response make this undesirable

Collimating/filtering setup deployed at CAMS

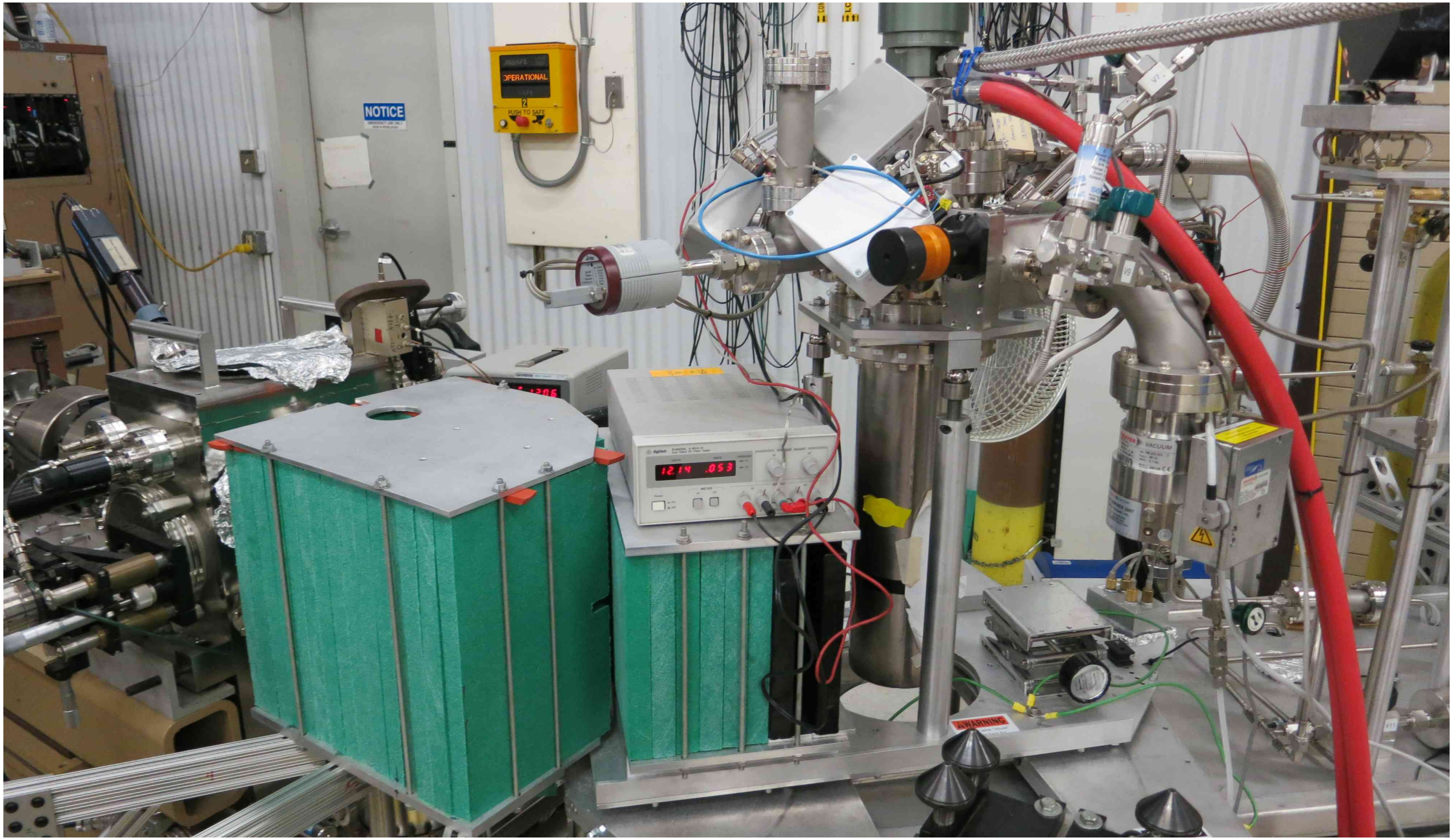
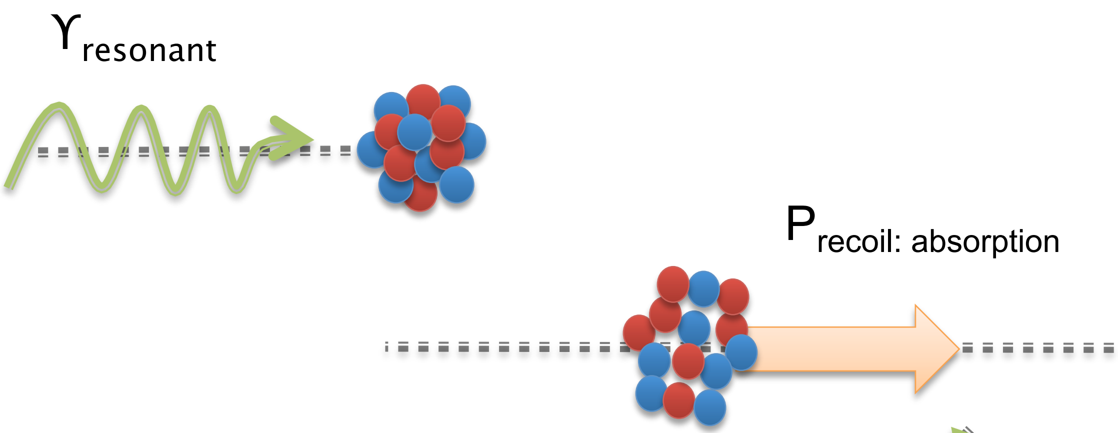


Photo-nuclear scatter as a source of nuclear recoils

- Act like a neutrino
  - Neutral
  - Massless
  - 1-10 MeV – Similar to reactor neutrinos
- Utilize resonant absorption to access benefits of photo-nuclear scatter (NRF)
  - Cross-sections are very large
  - Resonantly scattered gammas can be tagged in spectrometers
- Photo-nuclear scatter (Delbruck, Rayleigh, Tompson)
  - Much smaller cross-sections
  - Could be viable for higher Z nuclei

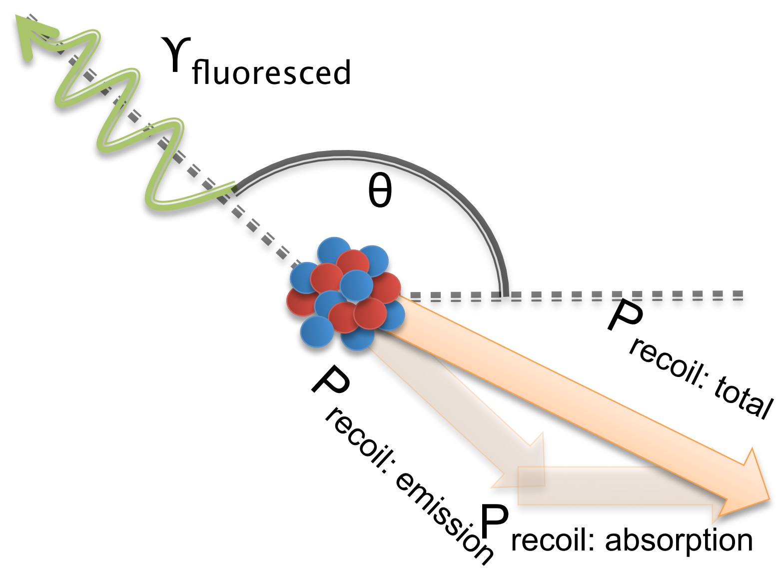
30-150 degree photonuclear recoil energies (eV)			
	3 MeV	6 MeV	9 MeV
Si	46-640	180-2600	415-580
Ar	32-450	130-1800	290-4000
Ge	18-250	72-1000	160-2200
Xe	10-130	40-530	85-1200

NRF as a source of nuclear recoils



$$E(\gamma_{fluoresced}) \approx E(\gamma_{resonant})$$

$$E(recoil_{total}) \approx 2Sin[\frac{\theta}{2}]^2 \frac{E_\gamma^2}{Mc^2}$$

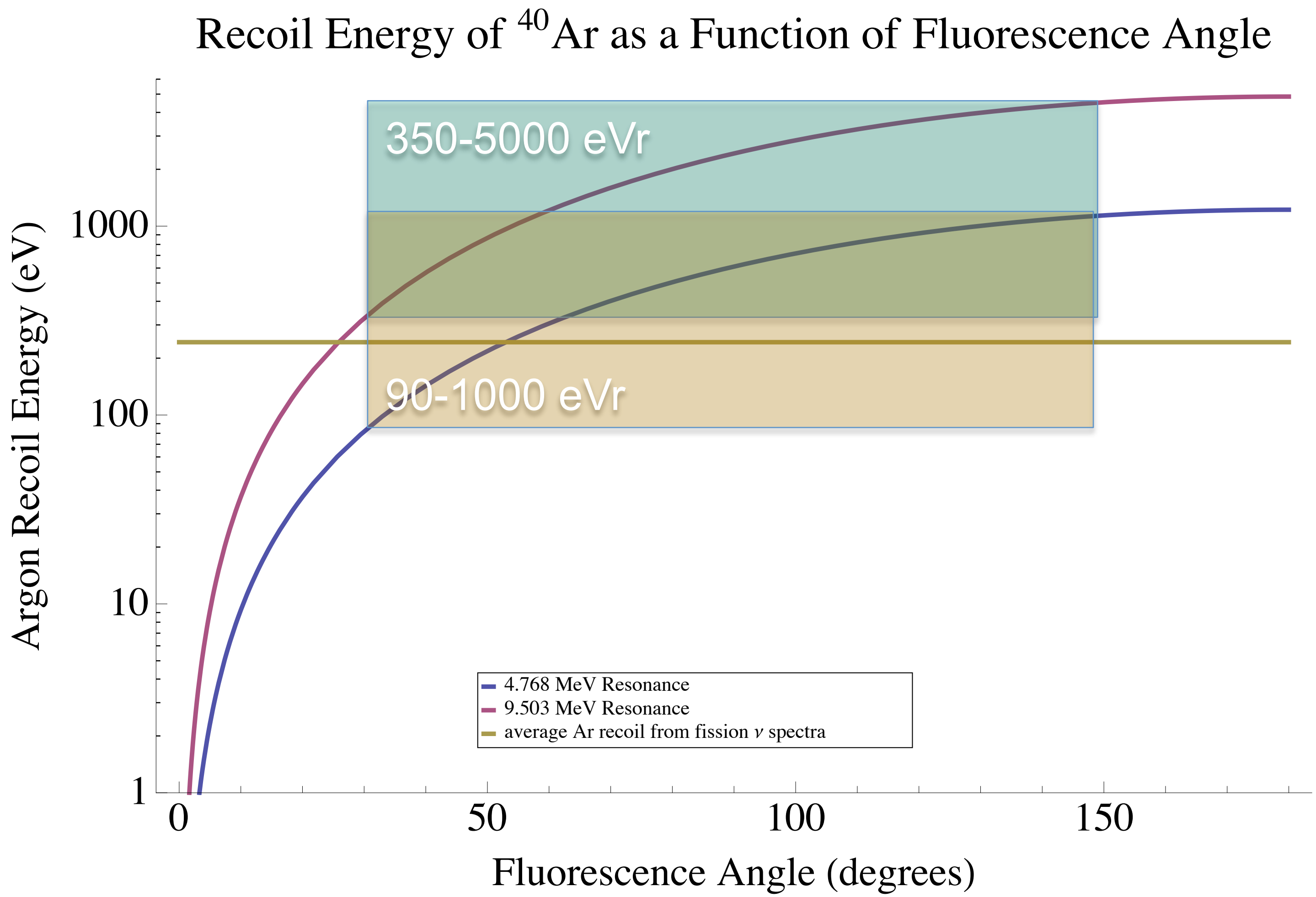


Identifying appropriate states

- Transition energy
  - 3-10 MeV
- E1 (or M1) transition
- Branching to G.S.
  - ~100%
- Short lifetime / large width
  - $\tau = \hbar / \Gamma$
- No or few neighboring states
- Width of the resonance, Γ
  - At least 1 lifetime before scatter on neighboring atom
  - $$\Gamma \geq \frac{10(\hbar c)E_\gamma}{Mc^2 * d}$$

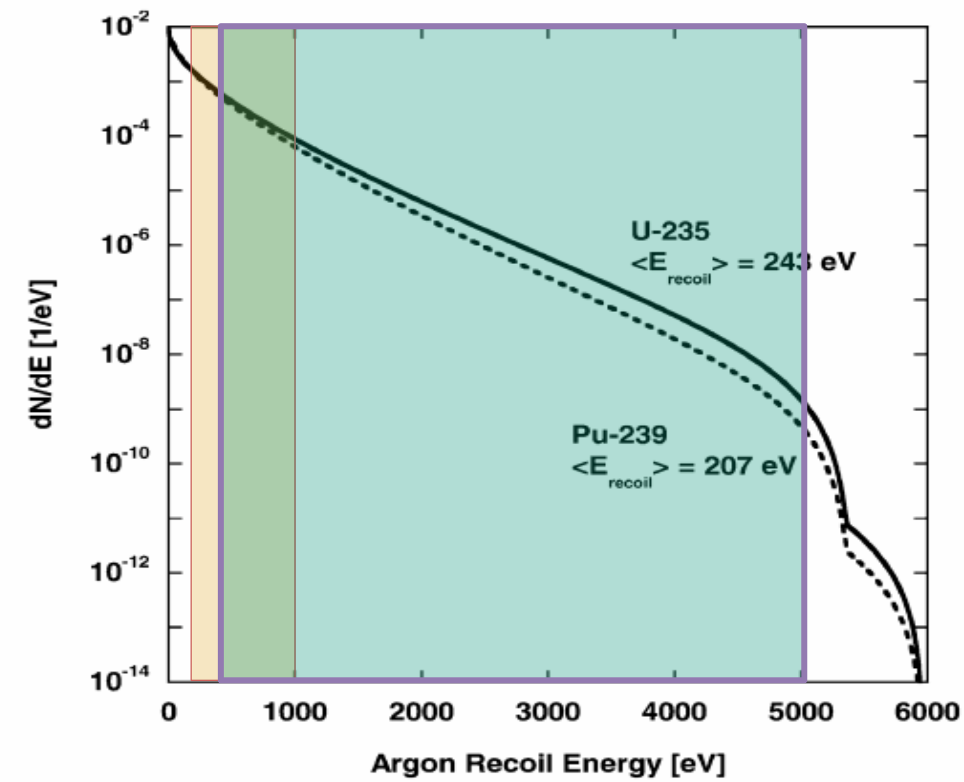
	4.769 MeV	9.503 MeV
J^π	1^-	1^-
Γ	0.82 eV	7.9 eV
G.S. Branch	100%	89%
τ	5.04 fs	0.52 fs
v_{recoil}	0.38 Å/fs	0.77 Å/fs
S/B	3	730
σ	405 eV barn	587eV barn

Probing the sub-keV in Argon



Fission neutrino regime can be characterized

Argon nuclear recoil spectra from fission ν's



Hagmann and Bernstein. *IEEE Trans. on Nucl. Sci.*, 51, 2151, 2004.

Gamma-tagging is needed to identify events

- Required to identify an event and recoil energy
  - Require moderate energy resolution
  - Reasonable stopping power to increase efficiency
- False triggers and backgrounds will be low (at reasonable angles)
  - Fluoresced gammas have incident gamma energy
  - Compton scatters are very forward peaked at MeV energies
  - Compton scattered photons are well below beam energy
  - Collimating the field of view can reduce pileup and elastic photon scatters from inactive regions

High Intensity Gamma-ray Source

- Duke Free Electron Laser Laboratory
- γ-Production: Compton backscatter
- Commissioned in 2007
- Polarization: horizontal and circular

- High Resolution Mode
  - Two asymmetric e^- bunches
  - ~1% Energy resolution
  - ~2×10^5 γ/sec at 4.769 MeV
  - 2.79 MHz collision frequency

Experimental challenges of NRF

- Experimental facilities are limited
- Backgrounds and noise
  - With current high energy photon sources the majority of incident photons are non-resonant
  - High rate of high energy Compton and Pair Production
  - Identification of these high energy events is easy, recovering quickly is difficult and
- Gamma-tagging array

Conclusions

- Producing controlled nuclear recoils in sensitive detectors is necessary to characterize CNNS target materials
- There are many ways to produce nuclear recoils, finding the best approach for your detector technology may not be immediately obvious
- We have proposed NRF as a source of sub-keV nuclear recoils in Argon
- **We have designed and built a collimated & filtered ^{7}Li(p,n) neutron source – currently being characterized**

Future Work

- Characterize $^{7}Li(p,n)^{7}Be$ neutron source with new thin Li target
- Measure ionization yield of few keV nuclear recoils in liquid argon
- Pursue possible application of the NRF technique for argon and other targets

**Acknowledgements

- Prof. Rick Norman
- LLNL, Penn State, Liverpool collaborators
- Lawrence Scholars Program
- DHS grant - ????

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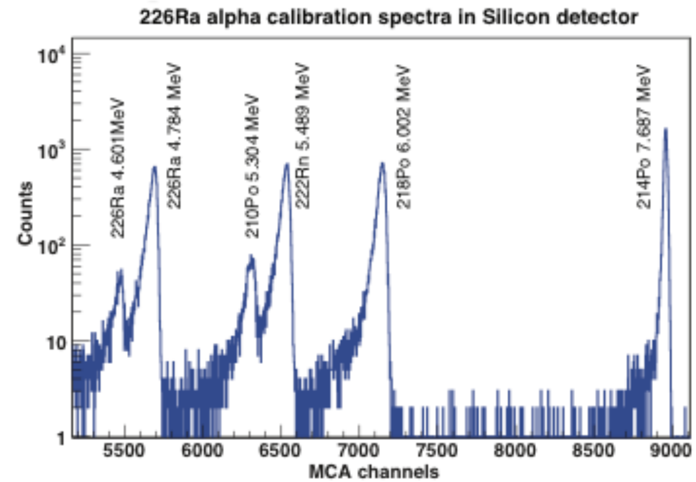
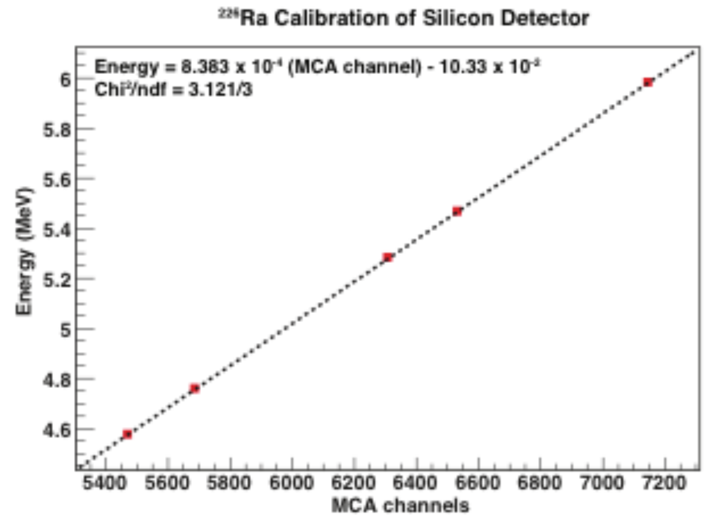
Verifying accelerator calibration

- Si-diode detector mounted on translation stage
- ^{226}Ra source mounted across from detector
- Calibrated detector immediately before and after measurement of proton beam





Correcting the terminal potential

- Measured very low current of protons at CAMS with calibrated Si-detector
- Observed 15 keV offset in terminal potential of accelerator